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Sensory evaluation and consumer acceptance of Kisra, a sudanese fermented flatbread made with biofortified sorghum: Insights from check-all-that-apply (CATA) method

Manhal Gobara Hamid [a,c], Claudia Böhme [b], Khitma Abdalha Mustafa [a,c], Yousif M.A. Idris [c], Faraz Muneer [d], Mohammed Elsafy [d,*], Mahbubjon Rahmatov [d], Eva Johansson [d], Tilal Sayed Abdelhalim [a,*]

[a] Biotechnology and Biosafety Research Center, Agricultural Research Corporation, Shambat, Khartoum, North Sudan
[b] Leibniz Institute for Educational Media/ Georg Eckert Institute (GEI), Braunschweig, Germany
[c] College of Agricultural Studies, Sudan University of Science and Technology, Shambat, Khartoum, North, Sudan
[d] Department of Plant Breeding, Swedish University of Agricultural Sciences (SLU), PO Box 190, 234 22 Alnarp, Sweden

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ABSTRACT

Kisra, a traditional fermented bread made from sorghum flour, is gaining prominence in Sudan's local food industry. This study evaluated the sensory attributes of nine Kisra products prepared from five sorghum cultivars, including the biofortified Dahab variety, rich in iron and zinc. Cultivars tested included Wad Ahmed, Dabar-Tabat, Korokolo, and Arfagadamek-8, along with their 1:1 blends with Dahab. Skilled local women prepared the Kisra to ensure authenticity. Sensory characteristics such as appearance, taste, texture, color, and aftertaste were evaluated by 102 Kisra consumers using hedonic and check-all-that-apply (CATA) tests. Data were analyzed using ANOVA, Tukey's test, hierarchical clustering, and correspondence analyses. Results revealed a preference for Kisra made from Dahab and Daber due to appealing traits like sweetness, smoothness, and porousness. Conversely, Korokolo and Arfagadamek-8 were less favored for their bitterness and coarseness. Consumer segmentation analyses highlighted Dahab's ability to meet sensory and nutritional needs. This study underscores the potential of biofortified sorghum in improving traditional fermented foods while addressing nutritional and sensory preferences, paving the way for more nutritious products in Sudan.

1. Introduction

Malnutrition remains a significant public health challenge, particularly in developing nations such as Sudan, where dietary deficiencies severely impact public health (Abu et al., 2019). Strategies to combat hunger have primarily focused on increasing farm yields and nutrient fortification, often overlooking traditional food processing methods that can enhance the nutritional quality of local foods, essential for reducing hunger and malnutrition (Materia et al., 2021).

Limited research has explored how traditional methods like fermentation improve nutrition and generate business opportunities, both essential for sustainable food systems (Golloso-Gubat et al., 2024). Fermentation, an ancient method that uses microbes to transform raw materials into food (Paul et al., 2023), is an invaluable skill often passed down through generations and predominantly practiced by women in Sudanese society.

Kisra, a traditional fermented thin-leavened bread made from sorghum flour, is a staple food in sorghum-growing regions, particularly in rural Sudan, and has cultural and nutritional significance. Its nutritional value is enhanced by the fermentation process using selected sorghum cultivars with high nutritional characteristics. Fermentation of Kisra involves lactic acid bacteria and yeast, which enhances Kisra's protein digestibility and improves the flavor and texture while reducing anti-nutritional factors such as phytic acid and increasing the bioavailability of essential nutrients such as iron, zinc, and calcium (AwadElkareem & Taylor, 2011; Makawi et al., 2019).

In Sudan, sorghum plays a crucial role in addressing nutritional and socioeconomic challenges, particularly in reducing malnutrition and stunting among children (Salim et al., 2017). Sorghum-based products, especially Kisra are rich in carbohydrates and proteins, essential for

* Corresponding authors.
E-mail addresses: Mohammed.elsafy@slu.se (M. Elsafy), tilalkosti@yahoo.com (T.S. Abdelhalim).

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growth and combating dietary deficiencies in a country with high child malnutrition rates (Hamad et al., 1992; Ibnouf, 2020; Mariod et al., 2016; TINAYSP et al., 1985). Kisra being gluten-free food, also meet the dietary needs of individuals with celiac disease or gluten intolerance (AwadElkareem & Taylor, 2011), and aligning with the global demand for gluten-free products. Aside from its nutritional values, Kisra significantly contributes to local economies by generating income opportunities for women, which are central to its production (Ibnouf, 2020; Makawi et al., 2019). Kisra is also a staple at communal events, reinforcing social bonds and promoting food sovereignty and sustainability through locally sourced ingredients (Materia et al., 2021).

Sorghum is a staple crop in Sudan; but, many varieties consumed today lack essential micronutrients, which contributing to malnutrition and diseases, such as rickets, scurvy, and anemia. Therefore, the biofortification of sorghum with essential micronutrients is a necessity for its nutrition value (Birol et al., 2015; MacDonald et al., 2017; Rizwan et al., 2021). The Sudanese Agricultural Research Corporation (ARC), introduced a new sorghum cultivar, Dahab (*Parbhani Shakti; SPV 1411* × *SPV 720*), developed by ICRISAT India in 2022. Dahab is enriched with iron (45 ppm) and zinc (32 ppm) to combat e micronutrient deficiencies in rural areas. While Dahab's has promising nutritional content, its success depends on consumer sensory acceptance, making a thorough evaluation of its sensory attributes critical for its adoption into the local food system.

Previous studies have shown that biofortification change the sensory profile of end-use products, which impacts consumer perceptions. The biofortification of orange-fleshed sweet potatoes with provitamin A resulted in changes in color, taste, and texture, that are critical for their acceptance by consumers in Mozambique (Badiane et al., 2018). Thus, adopting biofortified crops depends on meeting nutritional requirements and local culinary preference (Birol et al., 2015; Rizwan et al., 2021; Talsma et al., 2017). This is especially importance in Sudan, where understanding consumer preferences for biofortified sorghum, such as the newly introduced Dahab cultivar, is important for its successful adoption. Sensory evaluation is essential, as consumer preferences for taste, texture, and other attributes significantly influence the acceptances and consumption of sorghum-based products, ultimately impacting dietary diversity and nutrition (Isaacs et al., 2023).

Check-All-That-Apply (CATA) is an effective method for analyzing consumer preferences of Kisra because it captures nuanced perceptions, is user-friendly, and is versatile. In addition to simplifying sensory evaluation, it allows consumers to select multiple attributes, resulting in results comparable to those obtained by trained panels (Tiyo de Godoy et al., 2019). The use of CATA facilitates product development by revealing sensory drivers of liking (Rodrigues, Siman, de Oliveira, Barcelos et al., 2021) Its adaptability allows it to be integrated with other methodologies to improve consumer insight (Javier-Pisco et al., 2024).

This study aimed to 1) assess the consumer preferences for Kisra products made from the biofortified Dahab alone and its blend with other Sudanese sorghum cultivars using hedonic liking scores and check-all-that-apply (CATA) methods, and 2) provide breeders and seed specialists with precise visual maps linking high-quality sensory attributes to overall consumer liking. We hypothesized that Kisra made from Dahab would receive high ratings for key CATA attributes, providing insights for breeding sorghum cultivars with enhanced nutritional value and desirable sensory attributes for new product development.

2. Materials and methods

2.1. Ethical approval

The National Health Research Ethics Committee at the Federal Ministry of Health in Sudan reviewed and approved the research protocol, ensuring compliance with ethical standards for human participation. Written informed consent was obtained from all sensory panelists and adult consumers participating in the study. Before data collection, enumerators thoroughly informed participants about the study objectives, procedures, and their rights as participants. It was explained that their involvement was voluntary, and they could withdraw from the study without complications. Participants were also assured that their responses would remain confidential and only be used for research. These ethical measures were implemented to ensure the research process's integrity and protect participants' rights and well-being, in alignment with internationally recognized ethical guidelines such as the Declaration of Helsinki (https://www.wma.net/what-we-do/medical-ethics/declaration-of-helsinki/)

2.2. Sensometric approach

2.2.1. Materials

Grains of five sorghum cultivars, Dahab, Wad Ahmed, Dabar-Tabat, Korokolo, and Arfagdamek-8 were collected from Al-Gadarif Research Station during the 2023–2024 season for Kisra preparation and sensory evaluation. Dahab, a high-iron (Fe) and high-zinc (Zn) cultivar, was recently introduced in Sudan from ICRISAT India and officially released in 2022. The other cultivars, Wad Ahmed, Arfagadamek, Korokolo (all Feterita types), and Dabar-Tabat, were selected for widespread consumption and popularity among residents of Al-Gadareif state. For more information about the morphological group, pedigree, breeding status, year of release, pericarp color, and grain color of sorghum cultivars and landraces used for Kisra samples, see (Table S1).

2.2.2. Kisra preparation method

Grains from the five sorghum cultivars were thoroughly cleaned to remove any foreign material and debris and then milled into whole-grain flour using a commercial stone mill (100 % sorghum flour). Flour samples from each cultivar and four blends (1:1 ratio) of Dahab with Wad Ahmed, Korokolo, Arfa-Gadamek, and Dabar-Tabat were prepared for Kisra preparation.

To prepare dough (or "Ajin"), sorghum flour was mixed with water in a 1:2 (w/v) ratio in a traditional earthenware container called al Khumara (Zaroug et al., 2014). Fermentation was initiated by adding 10 % previously fermented dough as a starter, and the mixture was allowed to ferment at room temperature (25–27 °C) for 12–19 hours until it became cohesive and ready for Kisra preparation.

Kisra was prepared by pouring approximately 100–150 ml of thinned fermented batter onto a preheated (150–160 °C) flat steel plate (*Saj*). The batter was quickly spread onto a thin (1–1.5 mm) sheet, baked for 25–30 s, and then peeled off the plate. Kisra sheets were prepared from the remaining batter for each sample.

2.2.3. Participants

The sensory evaluation was conducted by 102 assessors from rural villages in Al-Gadareif state. Participants were free of health conditions affecting their sensory abilities (vision, touch, taste, or smell) and were regular consumers of sorghum Kisra, consuming it at least once every two weeks. Fresh Kisra samples (approximately 50 g each) were served to each panelist on white plates at room temperature to avoid visual bias. Each sample was coded using a unique identifier to ensure blind tasting. To maintain objectivity, the panelists were instructed to rinse the plates with water between the samples.

Sensory evaluation sessions were held mid-morning, from 10:00AM to 11:00AM, to minimize variations in sensory sensitivity due to hunger, fatigue, or circadian rhythms. The evaluations were conducted in a quiet, well-lit room with controlled temperature and humidity to ensure that environmental factors did not influence the results.

2.3. Sensory evaluation

A combination of sensory evaluation methods was used to assess consumer preferences, including the hedonic test, check-all-that-apply (CATA), CATATIS, and CLUSCATA. The hedonic test measured

consumer liking of Kisra samples on a 9-point scale, ranging from "dislike extremely" to "like extremely," providing quantitative data on overall satisfaction. The CATA method allowed participants to select attributes from a predefined list that best described each sample, capturing consumer-perceived sensory profiles. CATATIS was used to analyze the CATA data, comparing sensory attributes across samples and providing a detailed understanding of similarities and differences. CLUSCATA identified clusters of sensory attributes and consumer preferences, providing insights into group-specific perceptions. Together, these methods provided a comprehensive and evidence-based evaluation of consumer preferences and the sensory characteristics of Kisra products.

2.3.1. Hedonic test

In the hedonic test, 102 assessors from rural villages in Al-Gadareif state individually evaluated nine Kisra samples. The samples were presented in a randomized order to minimize bias. Assessors were instructed to identify the sensory attributes that best matched their perception of an ideal Kisra product, focusing on touch, smell, and taste. After this evaluation, they rated their overall liking of each sample using a 9-point Likert scale.

2.3.2. Check-All-That-Apply (CATA)

The CATA test investigated the relationship between overall liking scores and the frequency with which specific sensory characteristics were identified. After evaluation their overall liking, panelists selected the most and least appropriate sensory terms to describe each Kisra product. These terms included attributes related to appearance, odor, texture, taste, aroma, and aftertaste. This method enabled the identification of both positive and negative sensory attributes, offering insights into the most and least preferred qualities across the Kisra samples. (Table 2).

2.3.3. CATATIS

This study utilized the CATATIS (CATA Two-Table STATIS) method to analyze data collected from the CATA test, providing a quantitative measure of agreement among assessors. The method calculated a homogeneity index, which reflects the overall level of agreement within the panel and individual weights, indicating the extent to which each assessor aligned with the consensus (Llobell et al., 2024). These metrics are particularly valuable in consumer studies, where understanding variations in preferences and behaviors is critical for identifying trends and developing products to meet consumer expectations. CATATIS provides a robust analytical framework for evaluating sensory perceptions and consumer preferences based on integrating these outputs.

2.3.4. CLUSCATA

CLUSCATA was applied to group assessors based on their responses in CATA terms. A hierarchical clustering approach followed by a k-means optimization was performed according to the procedures outlined by Castura et al. (2022). Atypical respondents were categorized and removed as a $K + 1$ cluster, which was subsequently excluded from further analysis. The homogeneity of responses within each cluster was then independently assessed to ensure consistency and reliability (Llobell et al., 2019). This method provided valuable insights into variations in consumer perceptions and preferences.

2.4. Data analysis

To evaluate consumer preferences, significant differences in overall liking scores among the Kisra samples were determined by one-way analysis of variance (ANOVA) using XLSTAT statistical software (version 2024, Addinsoft, New York, NY, USA). In this analysis, the overall liking score as the dependent variable, whereas the Kisra samples were the qualitative variables. Tukey's test was used for multiple comparisons to ensure a 95 % confidence interval. An internal preference mapping biplot revealed a diverse distribution of consumer feedback across the nine Kisra samples.

Euclidean distances and Ward's hierarchical cluster analysis (HCA) were employed to group customers based on their preferences. The analysis was extended by comparing data from the two assessors using clusters derived from the assessors' field and the horizontal format of the liking data. To further enhance understanding, an intelligence-pivot table in XLSTAT was utilized to correlate demographic profiles, such as age, gender, education level, and Kisra consumption frequency, with the overall liking scores.

Data from the check-all-that-apply (CATA) questions were analyzed following established protocols (Jaeger et al., 2015; Meyners et al., 2013). Each CATA term's frequency was calculated, and Cochran's Q test was applied to identify significant differences among Kisra samples based on binary attributes (Cochran, 1950; Meyners et al., 2013). The Sheskin test was employed for post-hoc pairwise comparisons to evaluate the product discriminability (Sheskin, 2003). Contingency tables, constructed to intersect Kisra samples and CATA terms, form the basis for correspondence analysis (CA), which examines the association between Kisra samples and sensory terms (Greenacre, 2017; Meyners et al., 2013). Additionally, principal coordinate analysis (PCoA) assesses the distribution of preference scores linked to specific attributes, providing further insights into consumer feedback.

A penalty lift analysis was conducted to link hedonic liking scores with CATA terms. A 10 % citation frequency threshold was used for general analysis, while 20 % was employed to compare consumer groups with Kisra consumption frequencies (Meyners et al., 2013). Positive penalty values indicated sensory attributes that enhanced liking, whereas negative values indicated a reduction in preference. Attributes were classified into three categories: Essentials (attributes whose absence caused a significant drop in overall liking (OL)), To Avoid (attributes whose presence caused a significant drop in OL), and 'Nice--to-Have (attributes that caused only a minor drop in OL when missing). This analysis provided actionable insights into sensory attributes that drive consumer preferences, guiding potential product modifications to better align with consumer expectations (Ares et al., 2014).

3. Results

3.1. Demographic information

A total of 102 assessors participated in the sensory evaluation of the nine Kisra products. Of these, 86 assessors (84 %) were female and 16 % ($n = 16$) were male (Table 1). The majority of participants (46 %, $n = 47$) had completed primary school education, followed by those with secondary school education (21 %, $n = 21$) and a bachelor's degree.

Table 1
The demographic characteristics of the assessors who participated in the sensory evaluation of nine Kirsa samples of five sorghum cultivars and blends.

Variable	Categories	Frequencies	%
Gender	Female	86	84.0
	Male	16	16.0
Education	Bachelor's degree	21	21.0
	Intermediate school	13	13.0
	Primary school	47	46.0
	Secondary school	21	21.0
Age	18–30	44	44.1
	31–40	24	23.6
	41–50	19	18.6
	51–60	13	12.7
	61–70	2	2
consumption	3–6 times a week	26	25.5
	More than once a day	28	27.5
	Once a day	21	20.6
	Twice a month	2	2.0
	Twice a week	25	24.5

Additionally,13 % (n = 13) of the assessors attended intermediate school.

The assessors' ages ranged from 18 to 70 years. The largest age group (45.1 %, n = 46) fell within the range of 18 - 30 years, followed by 31- 40 years (21.6 %, n = 22), and 41 - 50 years (18.6 %, n = 19). However, the 51–60 years group accounted for 12.7 % (n = 13), while only 2 % (n = 2) of the assessors were between 61 and 70 years of age (Table 1).

Regarding consumption patterns, 27.5 % (n = 28) reported consuming Kisra more than once a day, which was the most frequent consumption category. This was followed by 25.5 (n = 26) who consumed Kisra three times a week and 24.5 % (n = 25) who consumed it twice a week. Additionally, 20.6 (n = 21) consumed Kisra once a day, whereas only 2 % (n = 2) consumed it twice a month, making this the least frequent category (Table 1).

3.2. Overall liking of Kisra product samples

The overall liking scores of the nine Kisra samples varied significantly. Kisra, prepared from Daber and Dahab cultivars, received the highest overall liking scores, demonstrating strong consumer preference. Blends such as Dahab + Daber and Dahab + Korokolo had moderately positive scores, around one point above zero. Korokolo alone also scored positively but was rated lower than Daber and Dahab. A comparision of Kisra produced from Arfagadamek and Wad Ahmed cultivars, both standalone and blended, showed that Arfagademk-8 had the lowest overall liking score (Fig. 1A).

Principal component analysis (PCA) showed that the nine Kisra samples (blue points) were differentiated by assessors (red points) based on their sensory profiles, indicating a broad range of preferences (Fig. 1B). Principal component 1 (F1) accounted for 22.08 % of the total variance, while component 2 (F2) accounted for 16.72 %. Kisras from Daber and the Dahab + Daber blend were located in the upper right quadrant, showing a strong positive association with F1 and high preference. Likewise, Dahab appeared in the lower-right quadrant, which was a high preference. Kisra made from Korokolo, Wad Ahmed, and Arfagadamek-8, including their blends, clustered in the lower left quadrant, indicating a lower preference. Interestingly, Kisra made from Korokolo appeared in the upper-left quadrant of F2, indicating a niche preference by a smaller group of assessors.

Hierarchical clustering analysis (Fig. 2) grouped the 102 assessors into two main groups based on their overall preference of the 9 Kisra samples. Cluster 1 (blue) had 20 assessors, and exhibited shorter branch lengths, indicating a higher degree of similarity in preferences, likely favoring Kisra made from Daber and Dahab. Cluster 2 (red), which included 82 assessors, showed strong preferences to the Dahab + Daber blend and moderate to lower liking for cultivars such as Korokolo, Arfagadmek, and Wad Ahmed (Fig. 2).

3.3. Differences between assessor groups

The assessors in Cluster 1 rated Kisra from Dabar the highest (1.733), making it the most preferred product. The Dahab + Daber blend also received a high score (1.483), whereas Dahab alone had a moderate preference, with a score of 0.833, consistent with the Daber and Dabar+Dahab blend (Fig. 3A). Kisra products from Korokolo received lower positive scores, while those produced from sorghum cultivars with red-pericarps received the lowest scores, demonstrating they were the least preferred.

In cluster 2, Daber again received the highest score (0.279), followed closely by biofortified Dahab (0.267). The Dahab + Korokolo blend had a moderate score (0.194), while Wad Ahmed achieved a slight positive score (0.121). Compared to Kisra from Korokolo, Dahab + Arfagadamek, and Dahab + Daber blends had negative scores of −0.001, −0.196, and −0.099,. With Arfagademek having the lowest score of −0.526 (Fig. 3B).

Internal preference mapping for Cluster 1 explained 72.82 % of the total variance, with F1 accounting for 49.39 % and F2 for 23.43 % (Fig. 3C). Kisra made from Daber, Dahab, and their blend (Daber + Dahab) appeared on the far right of the biplot, showing strong positive correlations with F1 and a high overall preference. The Kisra made from Wad Ahmed and Arfagadamek's blends were positioned to the left, showing a lower preference for these blends. In F2,Kisra made from Korokolo and Dahab + Korokolo blend appeared in the upper quadrant, showing moderate preference Dahab and Dahab + Daber blend showed strong positive associations with F1 and F2, demonstrating their broad appeal (Fig. 3C).

For Cluster 2, the biplot predicted 37.10 % of the variance through F1 and 17.01 % throguh F2 (Fig. 3D). Kisra made from Dahab, Dabar, and the Dahab + Korokolo blend were positioned in the upper-right quadrant of F1, indicating strong positive correlations and high preference. The blends of Dahab + Wad Ahmed and Dahab + Arfagadamek appeared in the lower-right quadrant of F1, indicating a moderate preference. Compared to other cultivars, Kisra from Arfagadamek displayed distinct sensory characteristics (Fig. 3C-D).

Significant differences in liking scores between cluster 1 and 2 assessors were observed for Kisra from made from Daber, Wad Ahmed and

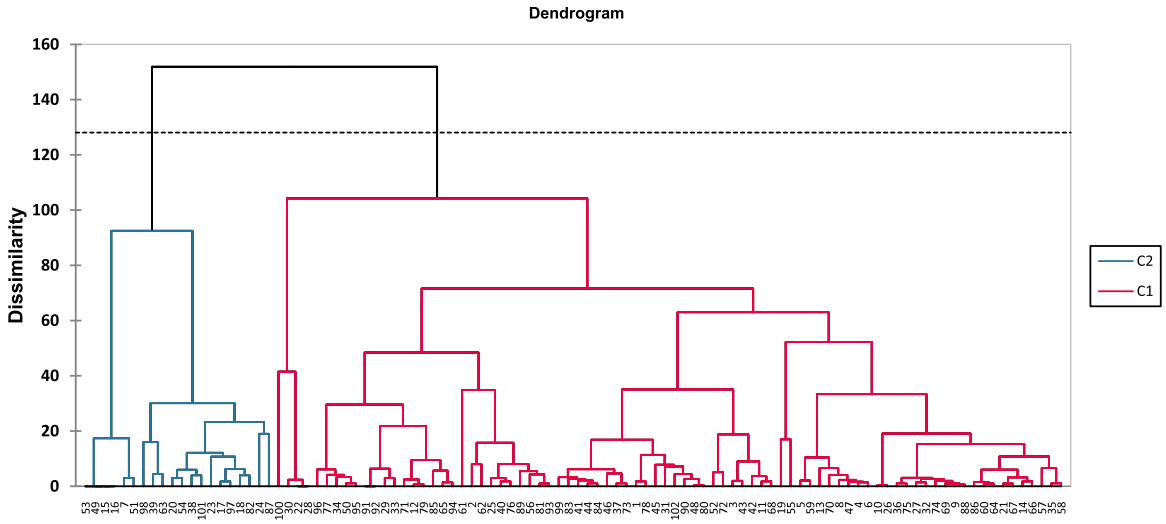

Fig. 2. Dendrogram obtained by Ward's methods using overall liking data of nine Kirsa samples. The Dendrogram identified two major clusters based on similarity of 102 assessors.

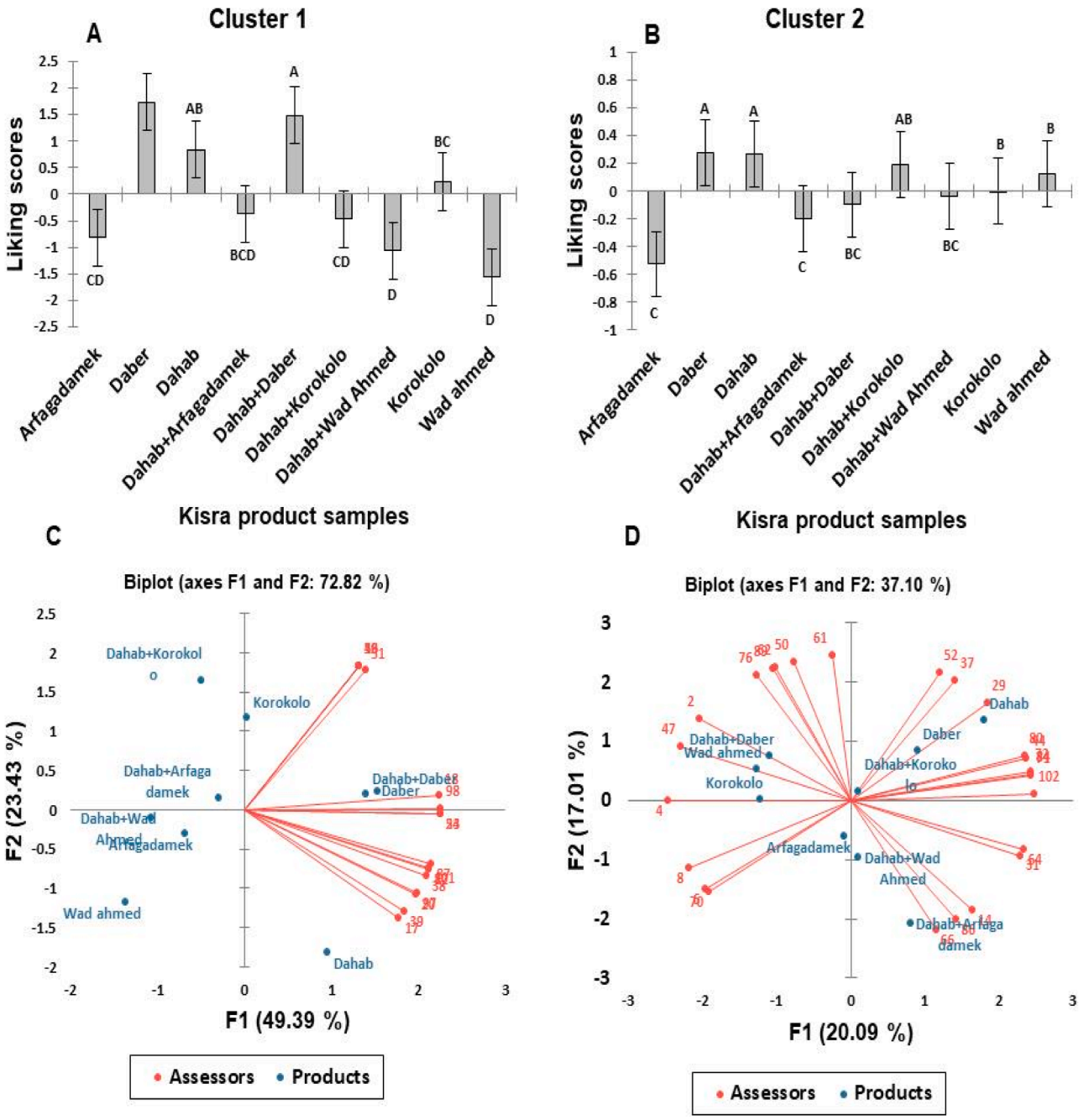

Fig. 3. Liking scores for the Kisra samples in cluster 1 (A) and cluster 2 (B) based on hierarchical clustering analysis. Biplot analysis showing the relationships between the Kisra product samples (blue points) and assessors (red points) for cluster 1 (C) and cluster 2 (D).

the blends (Dahab + Wad Ahmed, Dahab + Korokolo, and Dahab + Daber). Cluster 1 assessors rated Kisra from Daber and Dahab significantly higher, while Cluster 2 slightly preferred Kisra from Wad Ahmed. For the Dahab blends, the two clusters showed moderate scores. This suugests that individuals may respond differently to different types of Kisra, depending on the flavor components (Fig. 3A-D).

3.4. Contribution and percentage of demographic characteristics to overall liking of nine Kisra samples

The results show that consumption frequency had the most significant factor influencing overall liking, with a value of 100 and a contribution of 55.8 %. This finding indicates that frequent Kisra consumers rated the samples more favorably. Age was the second most influential factor, with a value of 35 (17.85 %), followed by education, which contributed approximately 28 (14.5 %). The sex factor had the least influence, with a value of 23 (11.9 %) (Fig. 4).

3.4. Check-all-that-apply (CATA)

The CATA evaluation of the nine Kisra samples, made from five Sudanese sorghum cultivars and their blends, showed significant differences in sensory attributes. Of the 27 attributes assessed, 12 showed significant differences based on Cochran's Q test, $p < 0.05$), with most attributes exhibiting highly significant differences ($p < 0.0001$). Appearance attributes, such as porousness, lumpiness, and smoothness varied significantly, as did color attributes, such as lightness, darkness, reddishness, and yellowishness. Significant differences were also

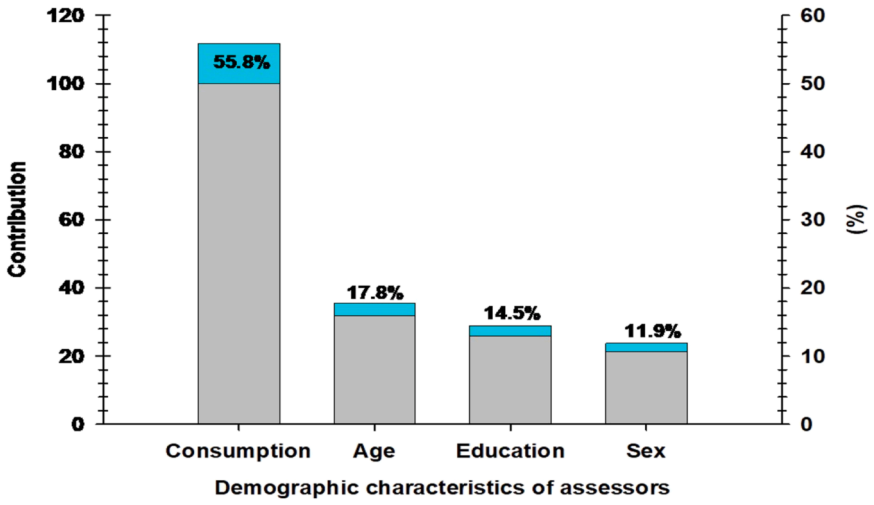

Fig. 4. Contribution and percentage of various demographic characteristics of assessors to the overall liking of Kisra samples.

observed in flavor attributes, including strong and weak flavors, sweetness, and sourness, also showd signficant differences. Among the texture attributes, cohesiveness was the only one that varied significantly, while aftertaste attributes showed no significant differences (Table 2).

The correspondence analysis (CA) explained 88.33 % of the total inertia, with F1 accounting for 76.06 % and F2 contributing 12.26 %. Kisra made from Daber and the Dahab + Daber blend were positioned in the upper-right quadrant, while Kisra from Dahab appeared in the lower-right quadrant, correlating attributes such as sweetness, strongness, porousness, and yellowishness. Kisra made from Daber and biofortified Zn- or Fe-enriched Dahab was preferred for its lightness, sweetness, and porousness. The bottom-left quadrant included Kisra from Wad Ahmed and Arfagadamek, which was associated with darkness, stiffness, bitterness, and reddishness. Kisra from Korokolo exhibited characteristics such as weakness, lumpiness, and cohesiveness (Fig. 5A).

Principal coordinate analysis (PCoA) based on correlation coefficients was used to evaluate the relationship between CATA attributes and overall liking (Fig. 5B). The results indicated that liking scores were closely linked to sweetness, lightness, porousness, and smoothness, reflecting consumer preference for Kisra products. In contrast, attributes such as bitterness, stiffness, lumpiness, darkness, and reddishness were the least favorable (Fig. 5B). Kisra made from Daber, Dahab, and their blend (Dahab + Daber) received the highest ratings, denonstrating the most desirable qualities.

According to the penalty lift analysis (mean impact), at consumer preference for Kisra products was strongly influenced by lightness,

Table 2
Counts of check-all-that apply (CATA)-based sensometric assessment of nine Kisra products made from 5 Sudanese sorghum cultivars and their blends.

Sensory dimensions	Attributes	AG-8	Dab	Dah	Koro	WA	Dah+AG-8	Dah+Dab	Dah+Koro	Dah+WA	Total	p-values
Appearance	Poreness	48	63	92	39	61	54	60	48	43	508	2E-16
	Lumpy	50	33	7	58	30	36	28	42	51	335	4E-16
	Smoth	43	57	71	41	35	41	45	36	33	402	6E-10
	Thickness	9	4	4	9	8	7	12	6	8	67	4E-01
Color	Lightness	16	72	54	27	9	23	52	23	14	290	0E+00
	Darkness	40	6	4	37	57	23	11	20	33	231	0E+00
	Reddishness	50	3	0	43	47	43	11	45	49	291	0E+00
	Greenish	3	3	3	2	5	4	3	3	3	29	1E+00
	Yellowish	3	17	61	6	0	4	25	3	1	120	0E+00
Flavor	Strong	44	49	68	37	48	42	46	42	53	429	4E-04
	Weak	36	36	21	42	37	39	38	37	30	316	4E-02
Taste	Sweetness	29	28	55	39	34	33	31	22	24	295	5E-07
	Sourness	30	43	44	23	31	31	40	26	33	301	4E-03
	Bitterness	10	4	3	3	7	11	3	5	8	54	5E-02
	Balance	28	21	15	21	19	20	16	25	22	187	3E-01
	Starchy	8	7	5	7	8	5	5	7	7	59	1E+00
Mouth Feel	Viscousiness	12	16	11	8	13	10	12	14	12	108	8E-01
	Hardness	7	6	6	8	7	4	4	8	6	56	9E-01
	Dryness	6	2	3	5	5	3	4	9	6	43	5E-01
	Coarseness	9	2	8	8	7	13	8	8	12	75	4E-01
	Stickness	5	2	8	6	6	7	4	7	10	55	2E-01
	Stiffness	0	1	1	4	4	5	1	2	6	24	5E-02
	Cohesiveness	17	21	8	11	16	6	16	12	10	117	4E-03
	Grinness	3	2	0	0	3	3	4	2	4	21	4E-01
After taste	Sweetness1	53	55	59	51	59	46	51	44	56	474	2E-01
	Sourness1	28	33	35	24	29	40	33	31	24	277	2E-01
	Bitterness1	7	3	5	8	3	8	3	5	4	46	5E-01
	Means	6.617647	7.7647	7.57843	7.245098	6.9902	6.9705882	7.4117647	7.26470588	6.9607843		

AG-8, Arfagadamek; Dab, Daber; Dah, the iron and zinc-enriched biofortified sorghum Dahab cultivar; Koro, Korokolo; WA, Wad Ahmed. Means; means of overall liking score. F. values with bold indicate significant differences between attributes according to Cochran's Q test for each attribute.

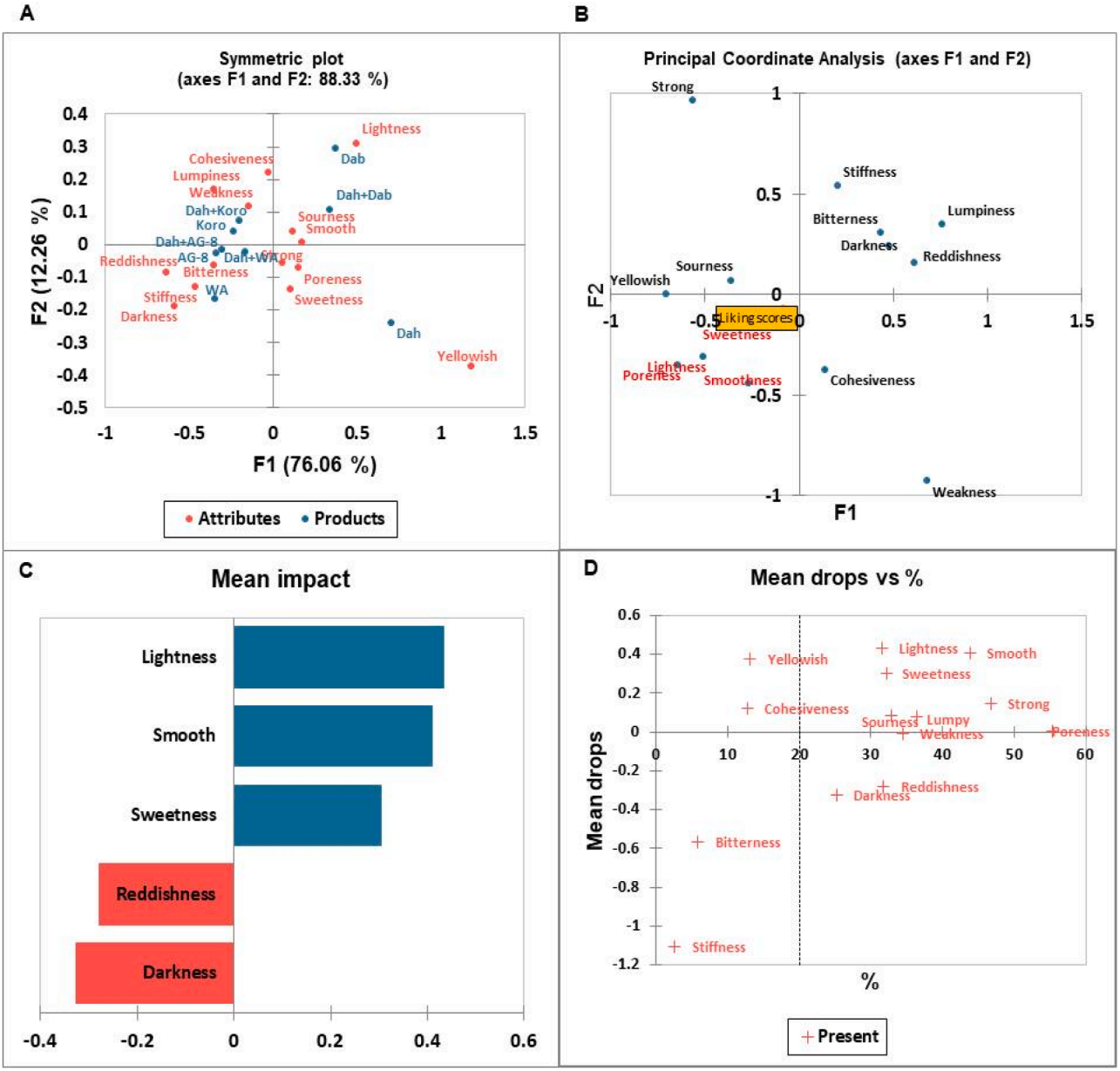

Fig. 5. CATA attributes and nine Kisra samples assessed according to correspondence analysis (A), principle coordinate analysis (B), penalty-lift mean impact analysis (C), and mean drop analysis (D). AG-8, Arfagadamek-8; Dab, Daber; Dah, Dahab; Koro, Korokolo; WA, Wad Ahmed.

smoothness, and sweetness, while reddishness and darkness negatively affected liking (Fig. 5C). An X-Y response graph evaluated the must-have attributes according to the mean drop (Fig. 5D). Lightness, smoothness, and sweetness were identified as positive drivers of liking, with high positive scores above 0.2. Reddishness, darkness, bitterness, and stiffness were the main negative drivers of overall liking (Fig. 5D).

3.5. CATATIS

Fig. 6 illustrates the distribution of assessor weights and their contributions to the overall liking and CATA attributes. Most assessors positively contributed to the consensus with minimal influence from outliers (mean weight 0.20; standard deviation, 0.0145). Assessors 5, 62, 70, and 86, whose weights were below 0.2, were identified as outliers, potentially introducing variability in the preference interpretation. The assessment results for assessors 3, 28, and 44 were more positive than the group's overall perception of Kisra and key CATA terms (S3_Figure 1). Results indicated a significant ($R = 0.52$; $P < 0.0001$) positive correlation between the assessor's number of checked attributes and weight obtained by CATATIS performed on the nine Kisra samples (S4_Fig. 2).

Based on CATATIS assessors weighted feedback, the biplot illustrates the distribution of Kisra products and CATA attributes. The two axes, F1 and F2, accounted for 82.9 % of the total variance, with F1 accounting for 70.26 % and F2 for 12.7 % (S5_Fig. 3). Kisra made from biofortified Dahab in the upper-right quadrant, was associated with positive attributes such as yellowness, sweetness, porousness, and strength, making it highly favorable. The Daber and Dahab + Daber blend in the lower-right quadrant, were linked to attributes such as lightness, sourness, and smoothness. Dahab + Korokolo and Dahab + Wad Ahmed blends were associated with negative traits, such as coarse texture, stiffness, and bitterness, making them less preferred. Wad Ahmed and Arfagadamek-8, on the center-left quadrant, were linked to reddishness, dryness, and stiffness, indicating low consumer preference.

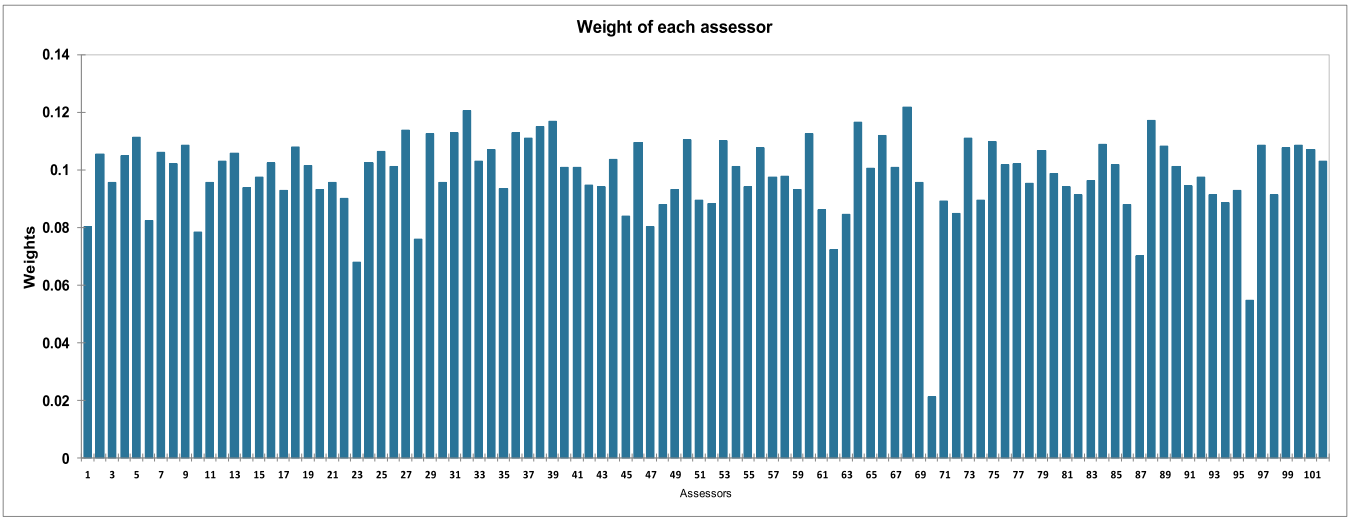

Fig. 6. The weights **αi (i** = 102) associated with the various subjects obtained by CATATIS.

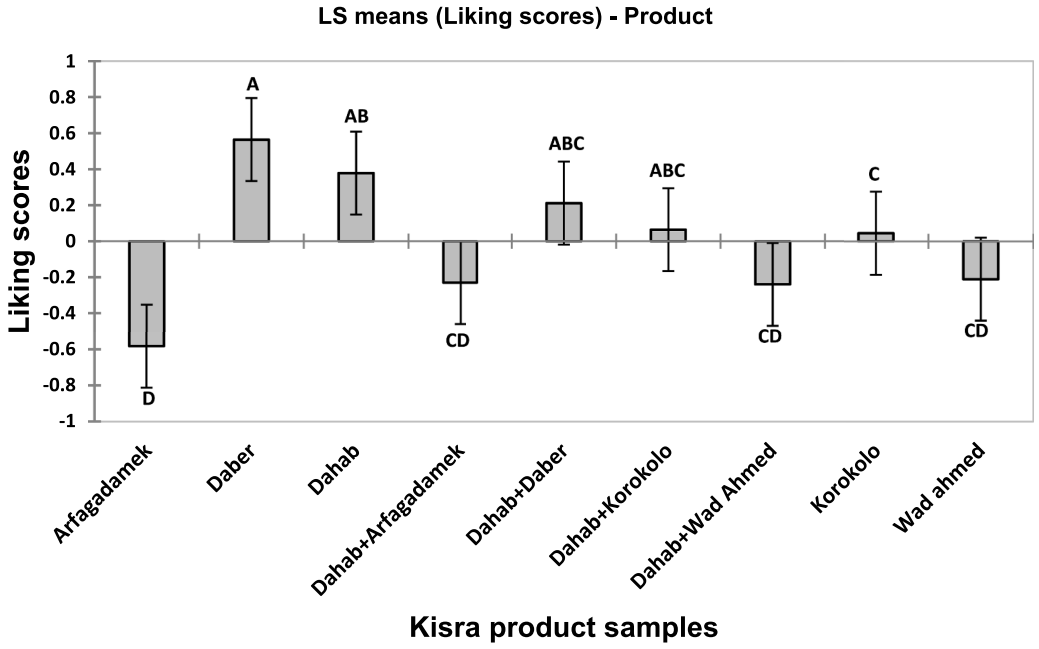

Fig. 1A. Comparative analysis of naive consumer overall liking scores for the 9 Kisra product samples evaluated by 102 assessors, detailing the least square means, along with standard errors. Distinctions in statistical significance are denoted by the different letters positioned above the respective bars.

3.6. CLUSCATA

In the initial phase, CLUSCATA was applied using a partitioning algorithm without identifying atypical assessors. Subsequently, the "$K+1$" approach detected 28 assessors as a part of the noise cluster (S6_Fig. 4). Removing these respondents increased the overall sample homogeneity from 45.0 % to 50.0 %.

Initially, Cluster 1 (C1) included 14 assessors with a homogeneity index of 41.9 %; Cluster 2 (C2) had 29 assessors with a 42.5 % homogeneity; and Cluster 3 (C3), the largest group with 44 assessors, exhibited the lowest homogeneity at 40.3 %. Cluster 4 (C4), comprising 15 assessors, achieved the highest homogeneity at 56.1 %. The weighted average homogeneity across all clusters was 45.2 %, whereas the global homogeneity was 43.5 % (S2_Table 2).

After applying the "$K = 1$" strategy, Cluster 1 was reduced to nine assessors with an improved homogeneity index of 50.2 %. Cluster 2 decreased to 21 assessors, maintaining a homogeneity of 47.8 %. Cluster 3 decreased to 30 assessors, and Cluster 4, with 14 assessors, achieved the highest homogeneity at 57.7 %. These adjustments increased the weighted average homogeneity to 50.2 % and the global homogeneity to 49.0 %, enhancing the overall clarity and consistency of the results (S2_Table 2).

Across all clusters, Kisra made from Dahab, Daber, and their blend (Dahab + Daber) was consistently preferred and associated with positive attributes such as smoothness, porousness, balance, and sweetness. On the other hand, Kisra products made from Korokolo, Arfagadmek, and Wad Ahmed (WA) were linked to negative attributes such as bitterness, reddishness, coarseness, and hardness (S7_Figure 5).

The correspondence analysis biplots illustrated the sensory evaluations of the nine Kisra products across four assessor clusters. F1, capturing 41.40 % to 53.75 % of the total variance, identified the key sensory attributes distinguishing Kisra products s, while F2, explaining 14.71 % to 20.42 %, provided additional insights into how assessors groups distinguished products and their CATA attributes (S7_Figure 5).

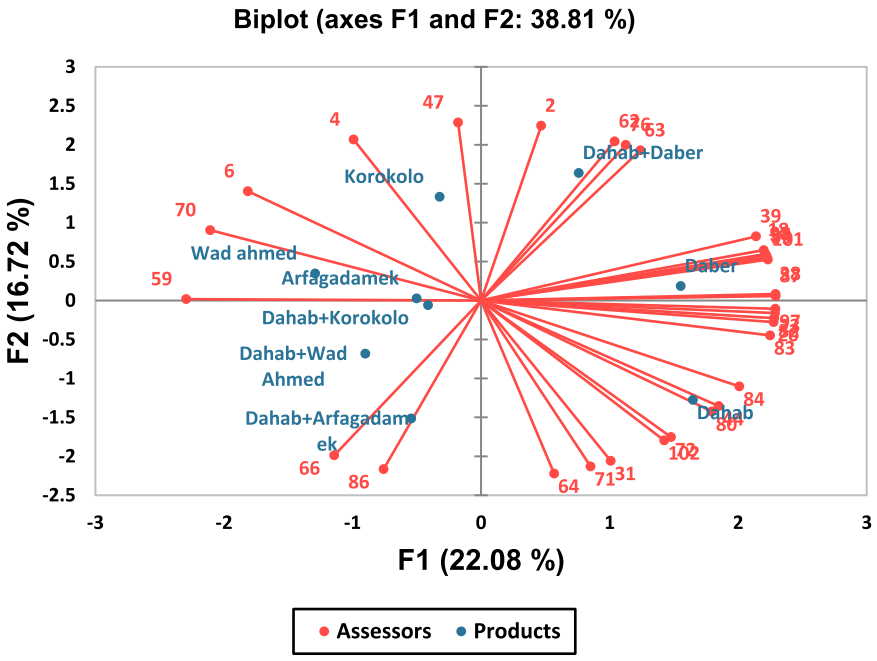

Fig. 1B. Internal Preferred mapping shows the relationships between the assessors (red points) and 9 Kisra product samples.

In Cluster 1 (68.46 % variance), Korokolo had low values due to negative attributes such as bitterness and coarseness, whereas Dahab and Dahab + Daber blend were highly preferred for their sweetness and smoothness (S7_Fig. 5A). In cluster 2 (66.65 % variance), the Dahab and Dahab+ Daber blend were positively associated with sweetness, whereas Wad Ahmed (WA) and Korokolo were linked to bitterness and grittiness (S7_Fig. 5B). Cluster 3 (73.53 % variance) reflected Dahab's preference for smoothness and balance, while Korokolo and AG8 were strongly associated with bitterness and hardness (S7_Fig. 5C). In Cluster (60.16 %), assessors preferred Dahab, Dahab + Daber blend, and AG-8 for their smoothness and mouthfeel, while Korokolo and Wad Ahmed were associated with bitterness and hardness (S7_Fig. 5D).

4. Discussion

This study evaluated consumer preferences for nine Kisra products made from various Sudanese sorghum cultivars and their blends. Assessors' demographic characteristics and consumption patterns provided a valuable context for interpreting sensory evaluation outcomes. Nine traditional Sudanese Kisra products were prepared using the biofortified sorghum cultivar Dahab and its 1:1 blends with other Sudanese sorghum cultivars.

Consumer preferences were assessed using hedonic overall liking scores and the CATA method, focusing on key sensory attributes, such as appearance, taste, mouthfeel, color, and aftertaste. The CATA methodology was chosen for its accessibility to untrained assessors who may lack the expertise required for more complex sensory evaluation techniques (Rodrigues et al., 2023; Rodrigues, Siman, de Oliveira, de Fátima Barcelos et al., 2021; Tiyo de Godoy et al., 2019). This approach reduces the cognitive load, making it particularly suitable for regions such as Sudan, where access to trained sensory panels is limited.

The CATA allows assessors to express their sensory perception effectively, making it a valuable tool for consumer-centered product development (Oliver et al., 2018; Rodrigues et al., 2023). Additionally, by measuring the sensory attribute intensity through citation proportions, CATA enhances the reliability of sensory evaluation (Gupta et al., 2021; Vidal et al., 2021).

The results indicate that consumers show a clear preference for Kisra prepared from the biofortified sorghum cultivar Dahab, underlining the potential of biofortification as a strategy to combat hidden hunger in rural Sudan and beyond. These findings are consistent with those of Birol et al. (2015), who demonstrated that consumers are more likely to accept biofortified varieties when they exhibit superior sensory qualities compared to conventional crops. This underscores the importance of incorporating consumer feedback into the development of biofortified sorghum-based food products to enhance acceptance and expand the market reach (De Groote et al., 2014; Razzaq et al., 2021). Additionally, effective marketing strategies that emphasize the nutritional benefits of fortified Kisra could further boost consumer acceptance and improve access to these products, particularly in rural households where anemia is prevalent.

The study found that consumption frequency was the most significant factor influencing overall liking scores for Kisra products, with frequent consumers assigning the highest mean scores. This aligns with Zhu et al. (2023), who reported that frequent fruit wine consumers showed stronger preferences than non-users, suggesting that consumption frequency shapes sensory expectations. Similarly, Rodrigues, Siman, de Oliveira, de Fátima Barcelos et al. (2021) emphasized the combined impact of sensory and contextual factors on consumer behavior. These findings offer valuable insights for food technologists and Sudanese women entrepreneurs seeking to promote Kisra adoption and satisfaction, especially for products made from biofortified sorghum.

This study demonstrated that age and education influenced assessor preferences, though to a lesser extent than consumption frequency. Younger and more educated assessors tended to rate Kisra products from the biofortified sorghum cultivars more favorably. These findings are consistent with Badiane et al. (2018) and Yeomans et al. (2020), who noted that younger individuals often have different preferences from older ones due to varying exposure to flavors and food experiences. Similarly, educational background affects an individual's understanding and appreciation of sensory attributes, influencing their hedonic ratings of food products (Rivaroli et al., 2023).

Interestingly, gender had the least influence on overall liking, with male and female assessors providing similar sensory evaluations of Kisra products. This finding contrasts with Chen et al. (2022), who reported that women generally exhibit higher olfactory sensitivity than men, potentially influencing their hedonic evaluations of scents and flavors.

Their research highlights the role of demographic factors in shaping sensory preferences and hedonic responses, emphasizing that gender can significantly impact product perception and assessment. Likewise, Iseki et al. (2021) demonstrated that gendered associations with scents can influence evaluations of tactile qualities, suggesting that semantic congruence between gender labels and sensory attributes may enhance hedonic responses.

Our findings identified two distinct clusters of assessors based on their overall preference for Kisra products, as determined through hierarchical clustering analysis. Cluster 1, consisting of 20 assessors, preferred Kisra products made from Daber, Dahab, and their blend, while Cluster 2, comprising 82 assessors, exhibited moderate or negative preference for these products. This division underscores the diversity of consumer preferences within what may initially appear to be a uniform group. Hierarchical clustering has proven to be effective in sensory studies, particularly when responses are varied and subjective (Meyners et al., 2013; Rodrigues, Siman, de Oliveira, de Fátima Barcelos et al., 2021). Moreover, combining hierarchical clustering with discriminant analysis can validate cluster assignments, provide clearer insights, enhance product development strategies, and improve consumer satisfaction.

Our findings underscore the critical role of sensory evaluation in understanding consumer acceptance and guiding the development of biofortified Kisra products within the traditional food sector. For example, consumers who prefer Kisra made from Dahab or unique blends characterized by sweetness, smoothness, porousness, and lightness may represent a distinct market segment. This highlights the interplay between sensory evaluation and market segmentation, particularly in the context of biofortified food.

Govender et al. (2019) emphasized that unfamiliar sensory characteristic of provitamin A-biofortified foods can hinder their acceptance, as consumers need to engage with and adapt to these sensory attributes for improved market access. Similarly, Chawafambira et al. (2021) noted that historical perceptions of yellow maize as animal feed in Zimbabwe have created barriers to its acceptance as a biofortified food, further illustrating the importance of addressing consumer perceptions in market segmentation strategies.

5. Conclusion

Kisra, either made from Dahab and Daber or their blend, was preferred for its sweet taste, smooth texture, lightness, and porousness. In contrast, Kisra products made with Korokolo and Arfagadamek-8 received lower acceptance scores due to less desirable characteristics such as bitterness, reddishness, and coarseness. These sensory characteristics may require adjustment to improve the market success of biofortified foods. Sensory analysis tools like CATA, CATATIS, and CLUSCATA effectively identified distinct consumer clusters and key sensory preferences, highlighting the strong potential of biofortified sorghum, particularly Dahab, to enhance nutrition while meeting sensory quality expectations. These findings support the development of Kisra products tailored for broader adoption in Sudanese markets and offer valuable insights for guiding future biofortification program in other countries.

Ethical statement

The National Health Research Ethics Committee at the Federal Ministry of Health in Sudan reviewed and approved the research protocol, ensuring compliance with ethical standards for human participation. Written informed consent was obtained from all sensory panelists and adult consumers participating in the study. Before data collection, enumerators thoroughly informed participants about the study objectives, procedures, and their rights as partcipants. It was explained that their involvement was voluntary, and they could withdraw from the study without complications. Participants were also assured that their responses would remain confidential and only be used for research purposes. These ethical measures were implemented to ensure the research process's integrity and protect participants' rights and well-being, in alignment with internationally recognized ethical guidelines such as the Declaration of Helsinki (https://www.wma.net/what-we-do/medical-ethics/declaration-of-helsinki/)

CRediT authorship contribution statement

Manhal Gobara Hamid: Writing – original draft, Methodology, Data curation. **Claudia Böhme:** Writing – review & editing, Funding acquisition. **Khitma Abdalha Mustafa:** Methodology, Data curation. **Yousif M.A. Idris:** Writing – review & editing. **Faraz Muneer:** Writing – review & editing. **Mohammed Elsafy:** Writing – review & editing, Validation. **Mahbubjon Rahmatov:** Writing – review & editing. **Eva Johansson:** Writing – review & editing. **Tilal Sayed Abdelhalim:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.afres.2025.100920.

Data availability

Data will be made available on request.

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